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Static Equivalent Seismic Analysis of Omo Sebua Traditional Timber Houses in Nias, Indonesia

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Abstract

Wooden houses located on Nias Island generally have not experienced damage to structural components when earthquakes have occurred in recent years. The purpose of this study is to conduct a static analysis of the existing Omo Sebua wooden house building located in South Nias, Indonesia. This study uses a three-dimensional structural analysis method with lateral loads modeled using the static equivalent method. Elastic moduli data of the main structural members were obtained from testing on the existing buildings. The research scope is limited to the structural analysis of buildings located in Botohilitano Village and Bawomataluo Village. The design earthquake load is calculated using the equivalent static analysis method. The design acceleration spectral response parameters use data according to the location of the building. The results of the analysis show that the drift that occurs in the building due to earthquake loads does not exceed the permit limits set by SNI 1726:2019. Drift limits range from 0.0014 to 0.0053, while deformation percentages obtained from analysis range from 14.3% to 52.9%, lower than the permitted limit. The ratio of bending moment of the main column to capacity ranges from 0.689 to 0.755, and the axial compression force ranges from 0.019 to 0.201. The ratio of bending moments of the main beam to capacity ranges from 0.204 to 0.375, and shear forces range from 0.056 to 0.099. The column and beam capacity can withstand the maximum factored load. The wooden columns resting on rocks also contribute to reducing the magnitude of earthquake load.

1. Introduction

Wooden houses located on Nias Island generally have not experienced damage to structural components when earthquakes have occurred in recent years. Existing wooden buildings that are currently decades old are generally still functioning well; there is no damage to structural components due to several earthquakes, namely in 2005, 2022, 2024, and 2025. This research focuses on the unique traditional wooden houses in Indonesia, the traditional timber houses located in Botohilitano village and Bawomataluo village in South Nias, located to the west offshore of Sumatra Island.

The purpose of this study is to conduct a static analysis of the Omo Sebua existing wooden house building located in South Nias, Indonesia. This study uses a three-dimensional structural analysis method with lateral loads modeled as static loads. Elastic moduli data of Simalambuo (*Lophopetalum sp.*) wood was obtained from testing on existing buildings. The scope of the research is the buildings studied are located in Botohilitano and Bawomataluo villages, South Nias, Indonesia. The design earthquake load is calculated using the equivalent static analysis method. The design spectral response of acceleration parameters in the short period (S_{DS}) and the design acceleration spectral response in the 1-second period (S_{D1}) use data according to the location of the building. Fig. 1 shows the location of Nias Island, located in North Sumatra Province, Indonesia. Botohilitano village is located at 0.5749, 97.7248, while Bawomataluo village is located at 0.6144, 97.7702.

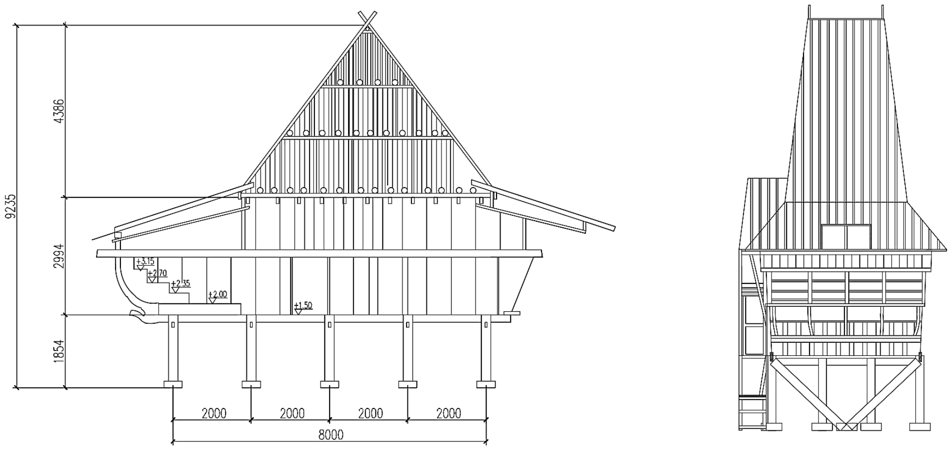
Fig. 1 *Location of the existing buildings on Nias Island*

The novelty of this research is the information on the seismic behavior of traditional Nias wooden houses, with the unique feature of diagonal bracing to enhance the building's stiffness. Diagonal bracing is a characteristic of traditional Nias wooden houses that is not found in other traditional wooden houses in Indonesia. The research gap lies in the limited studies on the modeling and structural analysis of traditional wooden houses with joint connections modeled as spring elements. The other novelty is the approach of the research by using the integration of non-destructive test data with static equivalent modeling to demonstrate an applied engineering application. This method could benefit from a clearer explanation of how findings influence seismic design or conservation strategies for traditional timber structures.

2. Previous Research and Basic Theory

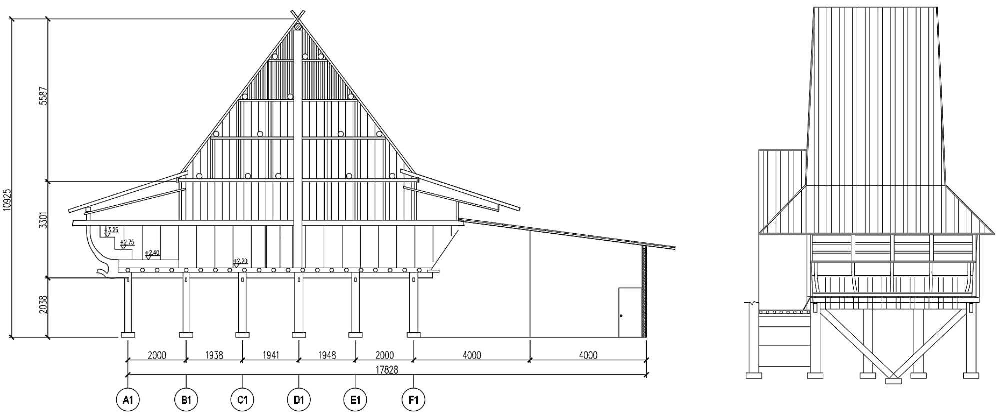
2.1 Nias Traditional Wooden House

Nias traditional wooden houses have a unique type of roof and unique diagonal bracing, and all the structural building members are made of timber [1]. Nias has a historical record of experiencing earthquakes in 2005, 2022, 2024, and 2025. Since several millennia ago, the island of Nias has been frequently rocked by seismic shocks followed by tsunami waves [2].



(a) **(b)**

Fig. 2 *The traditional house in Botohilitano Village (a) Front view; (b) Side view*



(a) **(b)**

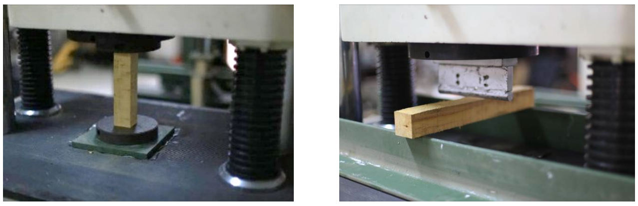
Fig. 3 *The traditional house in Bawomataluo Village (a) Front view; (b) Side view*

Fig. 2 shows existing wooden buildings named Omo Sebua in Botohilitano Villages and Fig. 3 shows existing wooden buildings in Bawomataluo Village. Both of this villages are located in South Nias Regency, North Sumatra Province. Based on explanations from homeowners and villagers, these buildings have been used as residences for more than 100 years [3]. The traditional Nias house in Bawomataluo Village is slightly different from the traditional Nias house in Botohilitano Village, namely the presence of two timber columns that continue from the top of the stone (elevation ±0.0) to the end of the roof of the house. The two timber columns are located right on each side of the house (see Fig. 3).

2.2 Mechanical and Physical Properties of Wood

In this study, several parameters of the mechanical properties of wood are required, namely elastic moduli, bending strength, and compressive strength. In addition, parameters of the physical properties of wood density are also required. Compressive strength, bending strength, and density are obtained from experimental testing in the laboratory with a destructive test method using the ASTM D143-14 codes [4].

Simalambuo (Lophopetalum sp.) wood's elastic moduli characteristics are determined using non-destructive testing. The structural elements of existing buildings' beams and columns were tested. The Sylvatest Trio instrument was used for testing [5], [6]. The test yields velocity parameters, which are subsequently transformed into dynamic elastic moduli parameters [7]. A static elastic modulus is then created using the dynamic elastic modulus parameters [8]. In the laboratory employing wood raw materials from Botohilitano village, Fig. 4 depicts the compression parallel to the grain and bending tests of wood using destructive methods. ASTM D143-14 codes are used in the test procedure [4]. The procedure of gathering velocity data on the current Botohilitano and Bawomataluo buildings using non-destructive testing techniques is depicted in Fig. 5. The main beams and columns were chosen as test points. Table 1 displays all of the earlier research findings.



(a) (b)

Fig. 4 *The compression and bending testing of wood* [3] *(a) Compression test parallel to the grain; (b) Bending test*

(a) (b)

Fig. 5 *The process of collecting velocity data on existing buildings with non-destructive testing methods (a) Botohilitano existing building; (b) Bawomataluo existing building*

Table 1 *Results obtained from tests* [3], [9]

Simalambuo (*Lophopetalum sp.*) properties	Value
Bending strength	25.1 MPa
Compression strength parallel to the grain	29.8 MPa
Specific gravity	0.45 gr/cm^3 or 450 kg/m^3
Elastic moduli	22973.1 MPa

2.3 Static Equivalent Analysis

The static equivalent analysis is a method in which a phase of analysis is carried out using nominal static lateral loads at earthquake loading. Static equivalent analysis was carried out with the aim of calculating the standard earthquake load pattern [10]. The purpose of static equivalent analysis is to simplify the actual lateral load into a horizontal force that acts on the center of mass of the building due to the lateral loads.

The static equivalent method is a simplified technique using a static force distributed laterally on non-story and multi-story buildings. The total force, which is base shear, is calculated in two main directions of the building. This method is relevant to low-rise and symmetric buildings [11]. The concept is to place an equivalent static load on a building with magnitudes and direction of the effects of lateral load caused by earthquakes. These lateral forces occur at floor and roof levels in the buildings, at the center of the mass of the building.

The static equivalent method simplifies dynamic earthquake forces into static (non-moving) lateral loads and is feasible, especially for low-rise buildings, by applying forces at floor levels proportional to mass and seismic coefficients. The static equivalent (earthquake) load in this study was determined using methods in compliance with the Indonesian earthquake code SNI 1726:2019 [12]. The Botohilitano building is located at coordinates 0.5749, 97.7248, while the Bawomataluo building is located at coordinates 0.6144, 97.7702.

$$T_0 = \frac{0.2 \text{ x } S_{D1}}{S_{DS}} \quad (1)$$

$$T_S = \frac{S_{D1}}{S_{DS}} \quad (2)$$

Where T_0 is calculated using 1, T_S is calculated using 2, S_{Ds} is the spectral response acceleration (short periods), and S_{D1} is the spectral response acceleration (a period of 1 second) [12]. As shown in Table 2, Peak Ground Acceleration (PGA) is the maximum acceleration of the mapped MCEG surface, S_s is the MCE spectral response acceleration of the earthquake map in the short period (5 percent attenuation), S_1 is the M_{CE} spectral response acceleration of the earthquake map in the period of 1 second, and T_L is a transition map for long period.

The parameters required for calculating the static base shear using design spectra data obtained from the Indonesian earthquake map [13] are shown in Table 2.

Table 2 *The parameters of design spectra data* [13]

Parameter	Botohilitano Building	Bawomataluo Building
PGA MCEG	0.60g	0.60g
S_S MCEr	1.50g	1.50g
S_1 MCEr	0.63g	0.62g
T_L	20.00 sec.	20.00 sec.
T_o	0.10 sec.	0.10 sec,
T_s	0.49 sec.	0.48 sec.
S_{DS}	1.20g	1.20g
S_{D1}	0.59g	0.57g

2.4 Structural Stiffness

According to the Indonesian earthquake code, residential buildings with residential functions fall within the fourth risk group [12]. The limit of deformation in the design of earthquake-resistant structures, or Δ_{max}, is categorized as other buildings, which can be calculated using Equation 3, where h_{sx} is the story height.

$$\Delta_{max} = 0.01 \text{ x } h_{sx} \quad (3)$$

2.5 Capacity of Structural Member

As structural components of wooden buildings, columns and beams can be designed using the Indonesian timber code SNI 7973:2013's Load and Resistance Factor method [14]. Equation 4 can be used to determine the design for factored compression load on the column member. Equation 5 can be used to determine the design for the factored bending moment for the beam and column members. Equation 6 can be used to determine the factored shear force design for the column and beam members.

$$P_u \leq P' \quad \text{where} \quad P' = F_c^{'}.A = F_c.C_M.C_t.C_F.C_i.C_p.K_F.\phi.\lambda.A \quad (4)$$

$$M_u \leq M' \quad \text{where} \quad M' = F_b^{'}.S_x = F_b.C_M.C_t.C_L.C_F.C_{fu}.C_i.K_F.\phi.\lambda.S_x \quad \text{and} \quad S = I_x / y \quad (5)$$

$$V_u \leq V' \quad \text{where} \quad V' = F_v^{'}.\frac{I_x.b}{Q} = F_v.C_M.C_t.C_i.K_F.\phi.\lambda.\frac{I_x.b}{Q} \quad (6)$$

where P_u is the column factored compression axial load (N), P' is the value of the adjusted compression axial force (N), F_c' is the value of the adjusted compression strength (MPa), A is the bruto column cross-section (mm^2), M_U is the factored bending moment (N.mm), M' is the value of the adjusted bending moment (N.mm), F_b' is the value of the adjusted bending strength (MPa), S_x is the elastic section moduli (mm^3)[15] , V_U is the factored shear force (N), V' is the value of the adjusted shear force (N) of the beam with a rectangular cross-section, F_v' is the value of the adjusted shear strength (MPa), Ix is the moment of inertia (mm^4)[15], [16] , b is the width of the beam (mm), and Q is the moment of static of the beam cross-section (mm^3).

The shear strength is required for the calculation of shear capacity. In this study, no destructive shear testing was carried out, so the shear strength was calculated using the Wood Handbook reference [17] using Equation 7, where G is the specific gravity obtained from wood measurements in existing buildings as shown in Table 1.

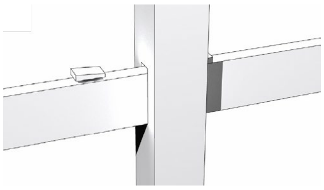
$$F_v = 21900.G^{1.13} \quad (7)$$

2.6 Rotational Stiffness for Modeling Column to Beam Connection

The Omo Sebua wooden building's column-to-beam timber connections exhibit some rotating motion and are not completely durable over time. An illustration of the column-to-beam connection of the current Botohilitano and Bawomataluo buildings employed in this study may be found in Figs. 6(a) and (b). Because the locking link between the column and beam creates the structural rigidity, Omo Sebua wooden constructions can function as regular or limited time-resistant frames.

(a)

(b)



(c)

Fig. 6 *Schematic model of column to beam connection (a) Existing joint of Botohilitano building; (b) Existing joint of Bawomataluo building; (c) Research by Moradei et.al.* [18]

Fig. 6(a) shows a schematic of the column-to-beam connection system. The moment and rotational stiffness of column-to-beam timber connections are in the range of pinned and rigid behavior [19]. The moment-rotational stiffness that was used for the column-to-beam timber connection in this modeling and structural analysis is obtained from research by Moradei *et al.* [18], which is 27 kN·m/rad as secondary data. The primary timber beam's cross-section in the outer layer of the timber column is used to measure moment and rotation. The steepest slope exhibits the stiffest moment-rotation behavior. This may occur as a result of the primary timber beam continuing through the opening of the timber column without weakening.

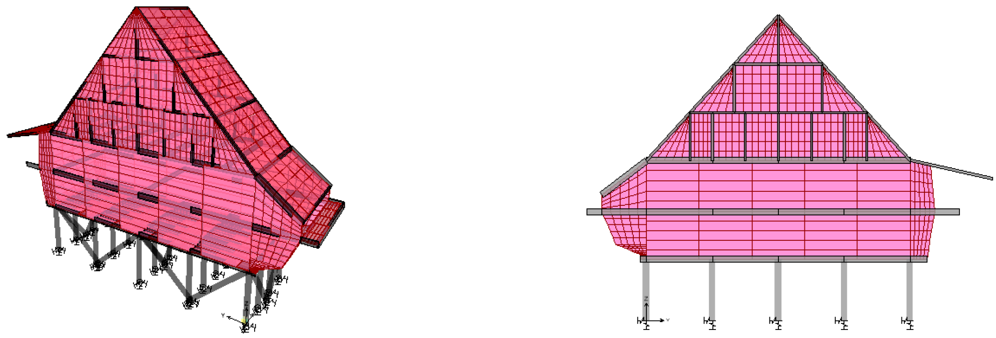
3. Methods of Structural Analysis

This study employed a three-dimensional structural analysis method that models lateral loads as static loads. Elastic moduli data of the existing Simalambuo (Lophopetalum sp.) wood was obtained from previous research [3], [9] using non-destructive testing on existing Botohilitano and Bawomataluo buildings. The mechanical properties that are used for the design of the capacity of column and beam members, which are bending strength and compression strength, are also obtained from previous research [3], [9]. The calculation of column and beam capacity refers to the requirements according to the wood code SNI 7379:2013 [14], and the building stiffness check refers to the earthquake code SNI 1726:2019 [12].

4. Results and Discussion

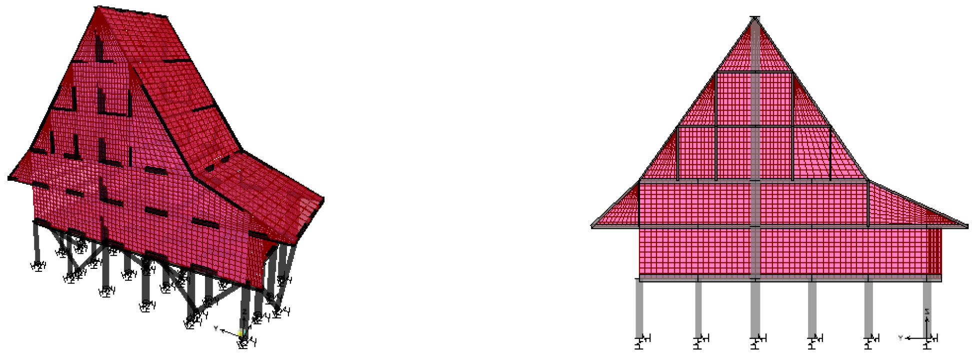
In this research, the building has dimensions as shown in Fig. 7 for a building that is located in Botohilitano village and Fig. 8 for a building that is located in Bawomataluo village, with the function as a residential house. Figure 8 shows a schematic 3D model including beams, columns, and roof systems. Numerical analysis of the 3D wooden structure was carried out using SAP2000 [20]. The walls are modeled as wooden planks with shell element types with elastic modulus parameters using test data on existing buildings [3]. Then the roof is modeled as a shell element without taking into account stiffness, with the aim of placing dead loads consisting of the self-weight of the roof structure and the roof covering made of rumbia leaves.

Existing wooden buildings in both Botohilitano and Bawomataluo villages use a foundation system, namely wooden columns resting on stones. The wooden column system resting on stones is then modeled in the structural analysis as a spring with a stiffness of 88.29 kN.m as secondary data from previous research by Suwantara & Rusli [21]. The type of stone (umpak) foundation that is often used in traditional wooden buildings is able to improve the overall structural performance due to lateral forces by reducing the lateral load 35% using justification of the friction coefficient by 0.35. This behavior is known as the base isolation system. The justification for using this parameter is based on the consideration that the spring stiffness was obtained from experimental testing of a wooden test specimen supported on a stone.



(a) **(b)**

Fig. 7 *Botohilitano existing building (a) Schematic 3D modeling; (b) Side view*



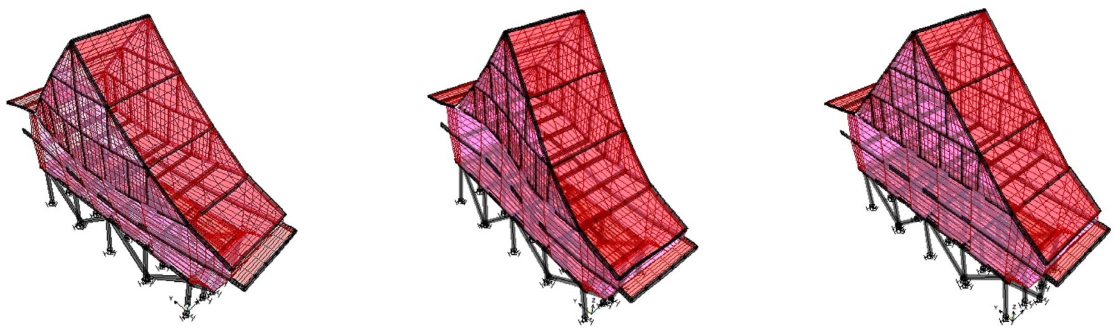
(a) **(b)**

Fig. 8 *Bawomataluo existing building (a) Schematic 3D modeling; (b) Side view*

The Bawomataluo building is different from the Botohilitano building, namely in the presence of two timber columns that continue from the top of the stone (first floor) to the end of the roof of the house, as shown in Fig. 8 and Fig. 3. The two timber columns are located right on each side of the house. The live load in terms of residential functions and the superimposed dead load used the reference from Indonesian loading codes [22]. Results obtained from modal analysis using SAP2000 software [21] are shown in Table 3, Fig. 9, and Fig. 10 with the result that the first and the third modes are translation in the two main direction of the building, while the second mode is rotation.

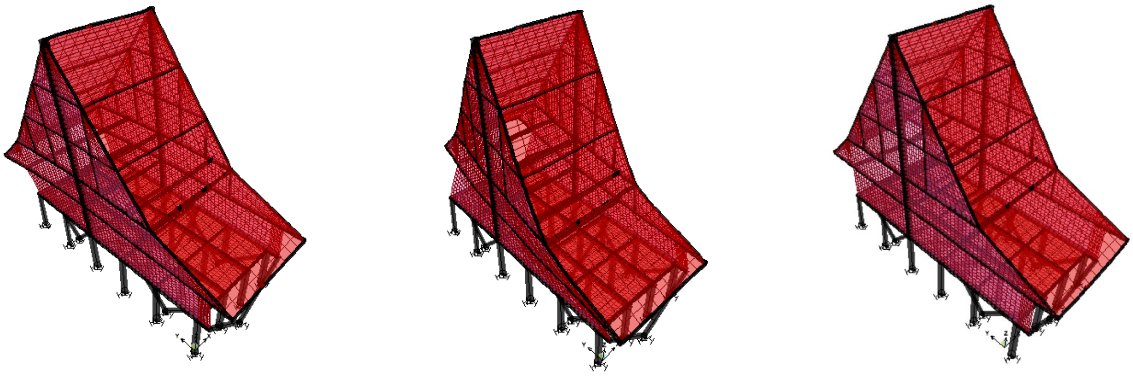
Table 3 *Results of the first three modes obtained from modal analysis*

Mode	Botohilitano building (sec.)	Bawomataluo building (sec.)
1	0.45	0.52
2	0.26	0.29
3	0.23	0.23



(a) **(b)** **(c)**

Fig. 9 *Botohilitano building (a) Mode-1; (b) Mode-2; (c) Mode-3*

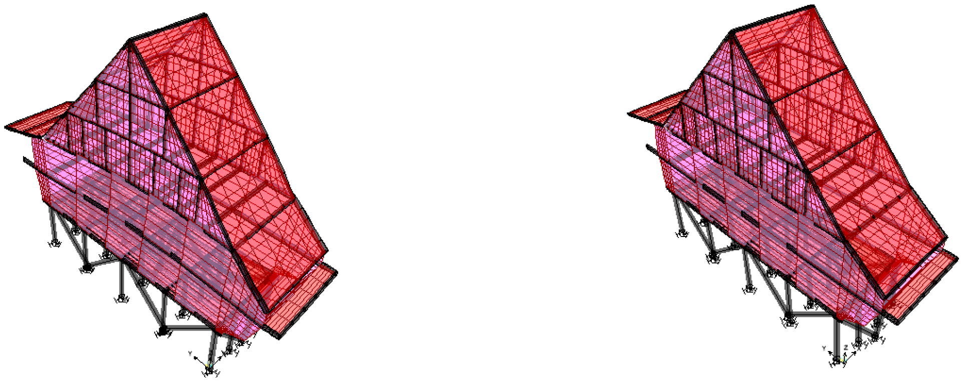


(a) (b) (c)

Fig. 10 *Bawomataluo building (a) Mode-1; (b) Mode-2; (c) Mode-3*

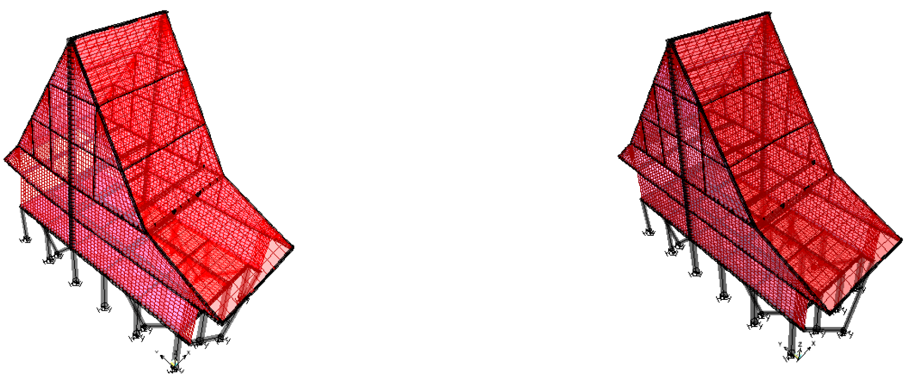
Fig. 11 and Fig. 12 show the lateral deformation shapes of the buildings due to the main x-direction and y-direction earthquakes. The results obtained from the analysis, which include the displacement of the structures due to designed lateral loads Ex and Ey in the two main directions, are displayed in Table 4 for Botohilitano buildings and Table 5 for the Bawomataluo building.

The lateral displacement of the Botohilitano building due to the designed earthquake load in the main two directions (x and y) at elevations +4.85 m and +9.24 m does not exceed the SNI 1729.2019 [12] permit limits. Likewise, the lateral deformation of the Bawomataluo building due to the designed earthquake load in the x-direction and y-direction at elevations +5.34 m and +10.93 m also does not exceed the permit limits.



(a) (b)

Fig. 11 *Deformed shape of Botohilitano building (a) Displacement-x; (b) Displacement-y*



(a) (b)

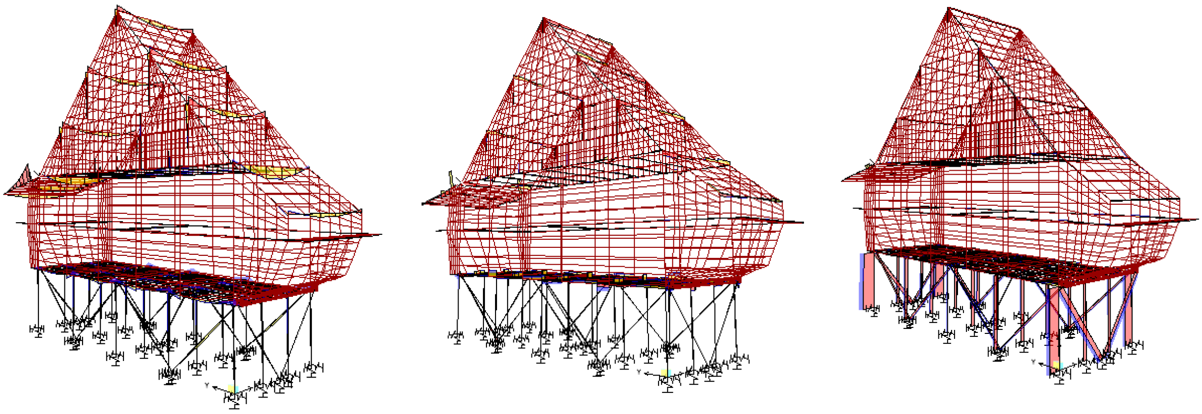
Fig. 12 *Deformed shape of Bawomataluo building (a) Displacement-x; (b) Displacement-y*

Table 4 *Results of displacement of Botohilitano building obtained from structural analysis*

Elevation (m)	Displacement-x (mm)	Drift-x (mm)	Displacement-y (mm)	Drift-y (mm)	Displacement Permission limits (mm)	Displacement percentage
+4.85	11.06	0.0023	22.63	0.0047	48.48	22.8% to 46.7%
+9.24	13.17	0.0014	45.78	0.0050	92.35	14.3% to 49.6%

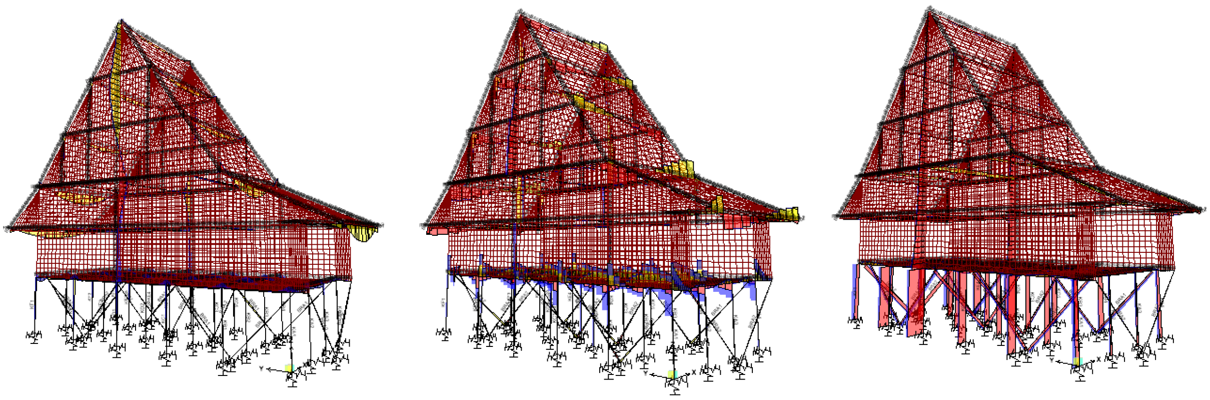
Table 5 *Results of displacement of Bawomataluo building obtained from structural analysis*

Elevation (m)	Displacement-x (mm)	Drift -x (mm)	Displacement-y (mm)	Drift -y (mm)	Displacement Permission limits (mm)	Displacement percentage
+5.34	19.21	0.0036	28.24	0.0053	53.40	36.0% to 52.9%
+10.93	48.04	0.0044	53.70	0.0049	109.30	44.0% to 49.1%



(a) **(b)** **(c)**

Fig. 13 *Internal forces of Botohilitano building (a) Moment; (b) Shear forces; (c) Axial forces*



(a) **(b)** **(c)**

Fig. 14 *Internal forces of Bawomataluo building (a) Moment; (b) Shear forces; (c) Axial forces*

Fig. 13 and Fig. 14 show the internal forces due to factored loads that contain live loads, dead loads, superimposed dead loads, and lateral loads on main beams and main columns, in terms of maximum loading combination. Next, these internal forces are compared to the capacity, which is calculated using Equations 4, 5, 6, and 7 according to the SNI 7973:2013 code [14]. The results as shown in Table 6 for the Botohilitano building and Table 7 for the Bawomataluo building indicate that the beam and column members have a higher capacity than the internal loads.

Table 6 *The calculation of the capacity of the main members of Botohilitano building*

Structural members	Parameter	Capacity	Internal Forces	Ratio of Internal Forces to Capacity	Status
Main column 1	P' (kN)	565.1	10.7	0.02	Ok
Circle cross-section, d = 150mm	M' (kN.m)	113.7	85.8	0.75	Ok
	V' (kN)	157.9	6.8	0.04	Ok
Main column 2	P' (kN)	565.1	10.8	0.02	Ok
Circle cross-section, d = 150mm	M' (kN.m)	113.7	12.5	0.11	Ok
	V' (kN)	157.9	4.6	0.03	Ok
Main beam 1	M' (kN.m)	57.2	17.3	0.30	Ok
Rectangular cross-section, 150/200mm	V' (kN)	119.1	9.1	0.08	Ok
Main beam 2	M' (kN.m)	38.1	12.3	0.32	Ok
Rectangular cross-section, 100/200mm	V' (kN)	79.4	7.9	0.10	Ok

Table 7 *The calculation of the capacity of the main members of Bawomataluo building*

Structural members	Parameter	Capacity	Internal Forces	Ratio of Internal Forces to Capacity	Status
Main column 1	P' (kN)	1004.7	201.5	0.20	Ok
Circle cross-section, d = 200 mm	M' (kN.m)	287.6	198.2	0.69	Ok
	V' (kN)	280.8	13.1	0.05	Ok
Main column 2	P' (kN)	565.1	68.9	0.12	Ok
Circle cross-section, d = 150 mm	M' (kN.m)	113.7	43.4	0.38	Ok
	V' (kN)	157.9	8.8	0.06	Ok
Main beam 1	M' (kN.m)	89.4	18.2	0.20	Ok
Rectangular cross-section, 150/250 mm	V' (kN)	148.9	10.8	0.07	Ok
Main beam 2	M' (kN.m)	38.1	14.3	0.38	Ok
Rectangular cross-section, 100/200 mm	V' (kN)	79.4	4.8	0.06	Ok

A general earthquake diagnosis method to evaluate behavior of wooden houses using the calculation of lateral load-carrying capacity [23]. The temperature of the area ranges from 25° to 36° Celsius. Since the wooden building has a low mass, which means it is equivalent to a reduced horizontal base shear load even during strong earthquakes, wooden buildings might be a good choice in high seismic zone regions [24], [25].

Drift limits range from 0.0014 to 0.0053, while deformation percentages obtained from analysis range from 14.3% to 52.9%, lower than the permitted limit. These results indicate that the building stiffness was significantly lower than the allowable limits when the earthquake load simulations were conducted.

The ratio of bending moment of the main column 1 to capacity ranges from 0.69 to 0.75, and the axial compression force ranges from 0.02 to 0.20. The ratio of bending moments of the main beam to capacity ranges from 0.20 to 0.38, and shear forces range from 0.06 to 0.10. These results indicate that the main components of wooden buildings, namely columns and beams, have a capacity ratio that is sufficient to channel the internal forces that occur due to simulated gravity and seismic loads.

Under real-world conditions, these two wooden houses in the Bawomataluo and Botohilitano areas did not experience permanent deformation failure during the 2005, 2009, 2023, and 2025 earthquakes [26] – [29]. The earthquake with the highest strength occurred in 2005 with a scale of M 8.6 [26], where no damage occurred to the structural components of the two buildings that were the objects of the research.

5. Conclusion

The results of the analysis show that the drift that occurs in the building due to earthquake loads does not exceed the permit limits set by SNI 1726:2019. The column capacity can withstand the maximum factored load in terms of bending moment, shear, and compression axial capacities. The main beam capacity can withstand the maximum factored load (shear capacities bending moment).

The wooden columns resting on rocks also contribute to reducing the magnitude of lateral forces (earthquakes). The system of umpak foundation that is often used in Omo Sebua timber buildings is able to improve the overall structural performance due to lateral forces, known as the base isolation system.

The contribution of this research to seismic design practice is the importance of using existing building material mechanical properties to investigate the behavior of existing buildings. For new buildings using the same type of wood, the mechanical properties information from nondestructive testing can be used as a reference by practitioners and academics in the design of new wooden buildings. Recommendations for future work include further study of the effect of wall stiffness made of wooden planks on building stiffness, thus improving the stiffness performance of wooden buildings.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Tani Frisda, Yosafat Aji Pranata;* ***data collection:*** *Yosafat Aji Pranata, Heri Lumban Tobing;* ***analysis and interpretation of results:*** *Yosafat Aji Pranata;* ***draft manuscript preparation:*** *Yosafat Aji Pranata. All authors reviewed the results and approved the final version of the manuscript.*

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